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ABSTRACT

A new ultrasonic technique aimed at simultaneously measuring the thickness and sound transit time in paper materials is presented. Two 1 MHz piezoelectric ceramic transducers immersed in water-filled rubber wheels are used to launch and receive signals transmitted through paper specimens inserted in the nip between the wheels. Time-delay analysis of the directly transmitted and rubber-paper interface reflection delayed signals provides the necessary information for thickness and transit time determination, from which the out-of-plane longitudinal sound velocity is calculated. Results are presented for paper grades from 50 to 1750 μm thickness.

KEYWORDS

Nondestructive evaluation; paper materials; thickness

INTRODUCTION

Thickness direction ultrasonic measurements in paper are difficult to achieve. Since this material has a relatively low acoustic impedance, internal reflections are hardly observable. This rules out pulse-echo techniques, and one has to rely on transmission measurements. Other difficulties in dealing with paper are the inadequacy of dry, hard-platen coupling due to surface roughness of paper and destructive liquid immersion testing. These problems can be alleviated by using a rubber interface as a compromise between hard-platen and liquid coupling [1, 2]. In this work, we present a new ultrasonic technique aimed at simultaneously determining the traveling path and time in the paper thickness direction, from which the out-of-plane longitudinal velocity can be evaluated. This technique, developed for on-line paper quality control in a paper mill, is based on the time-delay analysis of signals directly and indirectly transmitted through paper specimens using piezoelectric ceramic transducers immersed in water-filled rubber wheels. Measurement principles are first introduced. The experimental setup for the special case of static measurements is briefly described. Thickness and sound velocity measurements are then reported for various paper specimens.

MEASUREMENT PRINCIPLES

Consider the transmission mode arrangement shown in Figure 1 for nondestructive evaluation of paper specimens inserted in the nip between two surface conformable rubber layers. The left and right sides of the schematic represent the "reference" and "specimen" configurations, respectively. Two identical transducers are used to launch and receive ultrasonic signals. In practice, they are mounted on the axle of water-filled, molded urethane (hard-rubber) wheels. Specimens can be inserted in the nip by simply rotating the wheels. Water is used to provide acoustic coupling between the stationary transducers and the rotating wheels.

Assuming that the mechanical pressure between the wheels is large enough to minimize air gap effects, the transducers' separation distance is

$$d = d_1 + d_2 = d_{1'} + d_{2'} + \Delta d \tag{1}$$

where Δd is defined as the paper thickness (caliper). Since the signal launched from the transmitter travels through media having different acoustic impedances, time-delayed, reflected signals with respect to the directly transmitted signal (t_1 or $t_{1'}$ in Figure 1) occur. Only a few of these signals are of interest for evaluation purposes. Let's assume that d_1, d_2 and rubber thickness d_r are optimized in such a way that the reflected signal t_2 on the left side of Figure 1 is free of any interfering signals, traveling times for the reference signals t_1 and t_2 are described as follows:

$$t_1 = (d_1 + d_2 - 2d_r)/v_f + 2d_r/v_r \tag{2}$$

$$t_2 = (3d_1 + 3d_2 - 6d_r)/v_f + 6d_r/v_r \tag{3}$$

where v_f and v_r are the water (fluid) and rubber sound velocities, respectively. In a similar manner, traveling times for specimen signals as shown on the right side of Figure 1 are

$$t_{1'} = (d_{1'} + d_{2'} - 2d_r)/v_f + 2d_r/v_r + \Delta t \tag{4}$$

$$t_{2'} = (3d_{1'} + 3d_{2'} - 6d_r)/v_f + 6d_r/v_r + \Delta t \tag{5}$$

in which Δt is the transit time in paper. From equations (2) and (3), and (4) and (5), we get:

$$\delta t_{21} = t_2 - t_1 = 2(d_1 + d_2 - 2d_r)/v_r + 4d_r/v_r \tag{6}$$

$$\delta t_{2'1'} = t_{2'} - t_{1'} = 2(d_{1'} + d_{2'} - 2d_r)/v_r + 4d_r/v_r \tag{7}$$

Making use of (1) and subtracting (7) from (6), the specimen thickness is

$$\Delta d = v_f\,[\delta t_{21} - \delta t_{2'1'}]\,/\,2 \tag{8}$$

The transit time Δt is calculated from the subtraction of (2) from (4), i.e.,

$$\Delta t = (t_{1'} - t_1) + \Delta d/v_f = \delta t_{1'1} + [\delta t_{21} - \delta t_{2'1'}]\,/\,2 \tag{9}$$

The out-of-plane bulk longitudinal velocity is

$$v_z = \Delta d\,/\,\Delta t \tag{10}$$

EXPERIMENTAL SETUP

Two identical, custom-made, 1 MHz unfocused immersion piezoelectric ceramic transducers are used to launch and receive ultrasounds. As previously mentioned, they are mounted on the axle of free-to-rotate, water-filled, molded urethane wheels. The d_1/d_2 ratio is approximately 0.5. Rubber thickness is such that the reflected signals at the water-rubber interfaces do not interfere with t_2 and $t_{2'}$. The transducers' surfaces are isolated by a thin film instead of a quarter wavelength faceplate. In that manner, single-surface reflection takes place. The transmitter is excited with a variable amplitude 1 MHz, one-cycle sinusoidal signal. Received waveforms are preamplified and captured on a one-to-one basis with a 2432 Tektronix scope and transferred to a 386 computer for later analysis. Time resolution is 5 ns. Signal averaging is used to improve the S/N ratio. Paper thickness is accurately determined using a cross-correlation technique. Full-length waveforms are cross-correlated. Due to sound dispersion in paper, the frequency content of the reference and specimen waveforms is different. Hence, cross-correlating t_1 and $t_{1'}$ in equation 9 generates overestimated transit times (and underestimated velocities). In order to improve transit time measurement accuracy, a method based on waveform leading edge detection was developed. Leading edges are computed by first evaluating the time at first half-cycle maximum amplitude and then applying a time-correcting factor determined from the waveform center frequency.

RESULTS

In order to demonstrate the measurement capabilities of the water-filled wheels technique, data were gathered for 29 paper specimens from 50 to 1750 μm thickness at 50% RH and 23 ^{0}C. Specimens were divided into four categories: fine papers (including newsprints), linerboards, mediums and heavy weight boards. Figure 2 shows the "water-filled wheels" (WFW) thickness (equation 8) plotted as a function of the "soft-platen" (SP) thickness. The SP thickness involves neoprene coupling, and it is determined mechanically with a LVDT transducer. As a mean of comparison, "hard-platen" (HP) coupling data are included in the graph. As one should expect, best agreement is obtained with the SP thickness. In order to appreciate sound dispersion in paper, the directly transmitted waveform center frequency was evaluated as a function of the WFW thickness (Figure 3). We can see a clear tendency to lower frequencies for thicker samples. The dispersion uncorrected out-of-plane longitudinal velocity (equation 10) is depicted in Figure 4 as a function of a reference velocity obtained with the laboratory IPST out-of-plane ultrasonic velocity tester [1]. In the latter instrument, two neoprene-faced, broadband PVDF transducers are in direct contact with specimens. Good agreement is obtained for thick specimens only. Dispersion corrected velocity data are shown in Figure 5. While better agreement is now reached for thin specimens, this is no longer the case for thick samples. Since dispersion effects are neglected in the reference velocity calculations, this could account for the discrepancy denoted for thick samples. Apparent agreement for thin specimens can be explained by the fact that cross-correlation is applied over the waveforms' first half-cycle in the reference velocity transit time calculations, while full-length waveforms are used for the water-filled wheels transit time. First half-cycle cross-correlation results in reduced dispersion sensitivity for thin specimens only. Calibrated velocities are not available for paper materials.

SUMMARY AND CONCLUSIONS

Principles for a new ultrasonic technique based on transducers immersed in water-filled wheels have been described. Measurements reported at constant humidity and temperature for several paper specimens indicate that good agreement is achieved between water-filled wheels and soft-platen thicknesses. Due to dispersion in paper, out-of-plane sound velocity evaluation is problematic. However, consideration of dispersion increases the level of confidence in the velocity measurements obtained with the water-filled wheels technique.

ACKNOWLEDGEMENTS

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REFERENCES

1. Habeger, C.C. and Wink, W.A., Ultrasonic Velocity Measurements in the Thickness Direction of Paper J. Appl. Pol. Sc. 32:4503-4540(1986).
2. Habeger, C.C., Wink, W.A. and Van Zummeren, M.L., Using Neoprene-faced, PVDF Transducers to couple ultrasound into solids J. Acoust. Soc. Am. 84:1388-1396(1988).

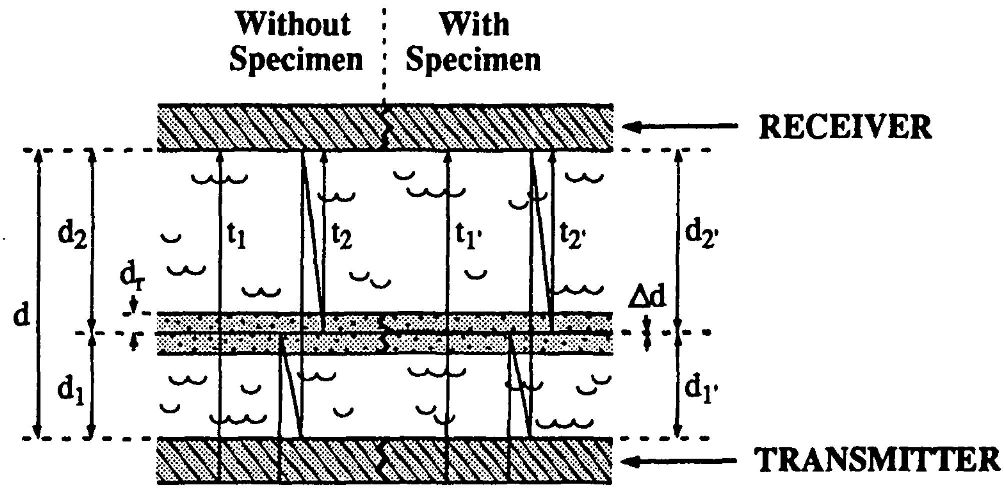

Figure 1. Schematic of the water-filled wheels measurement technique; left and right sides correspond to reference and specimen configurations, respectively.

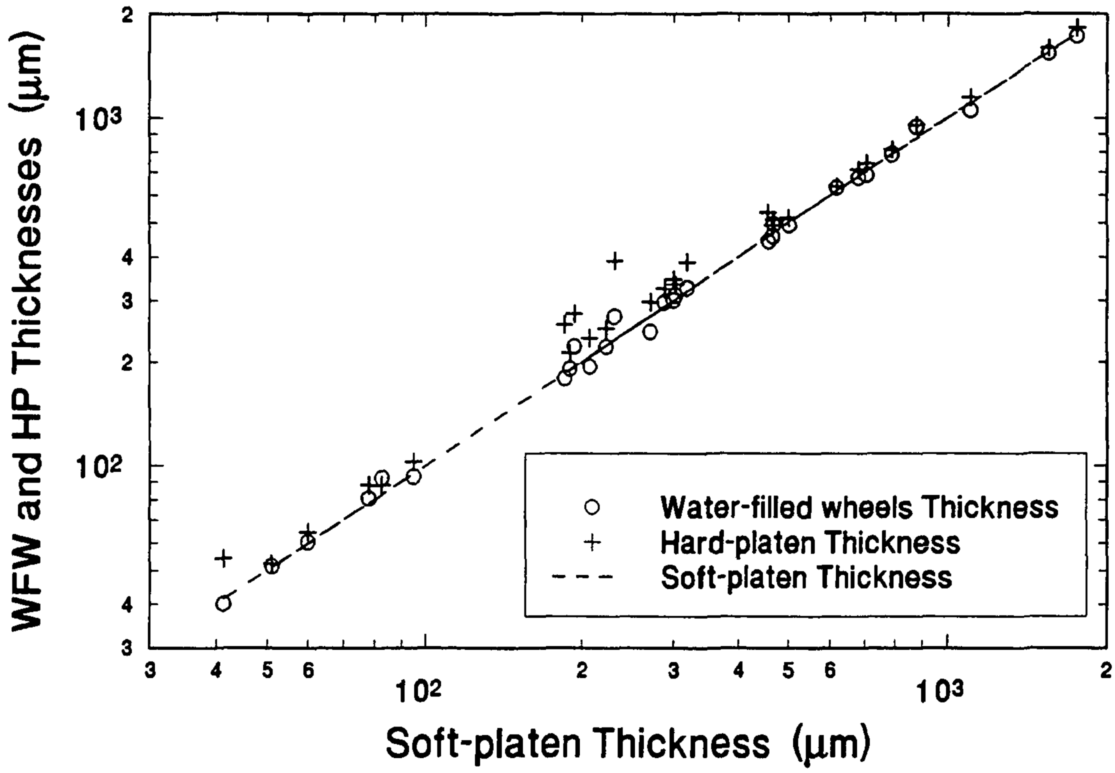

Figure 2. WFW and HP thicknesses vs. reference SP thickness.

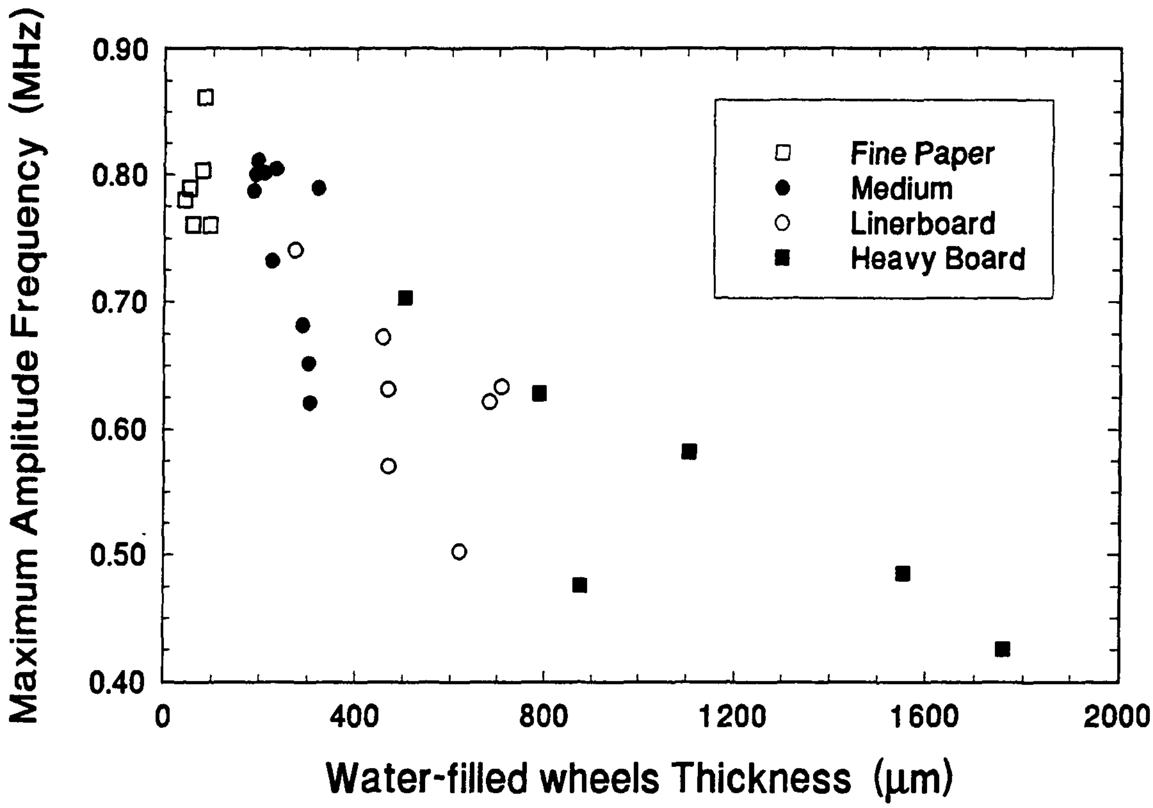

Figure 3. Directly transmitted waveform center frequency vs. WFW thickness.

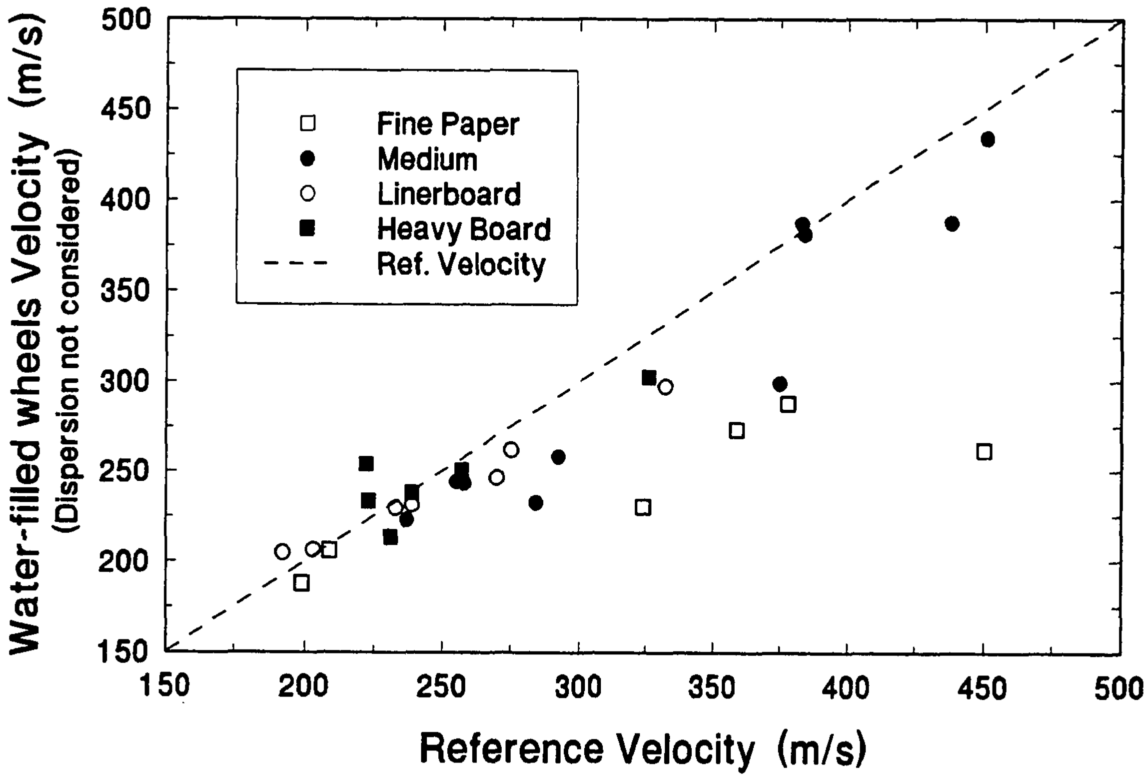

Figure 4. Dispersion uncorrected WFW velocity vs. reference velocity.

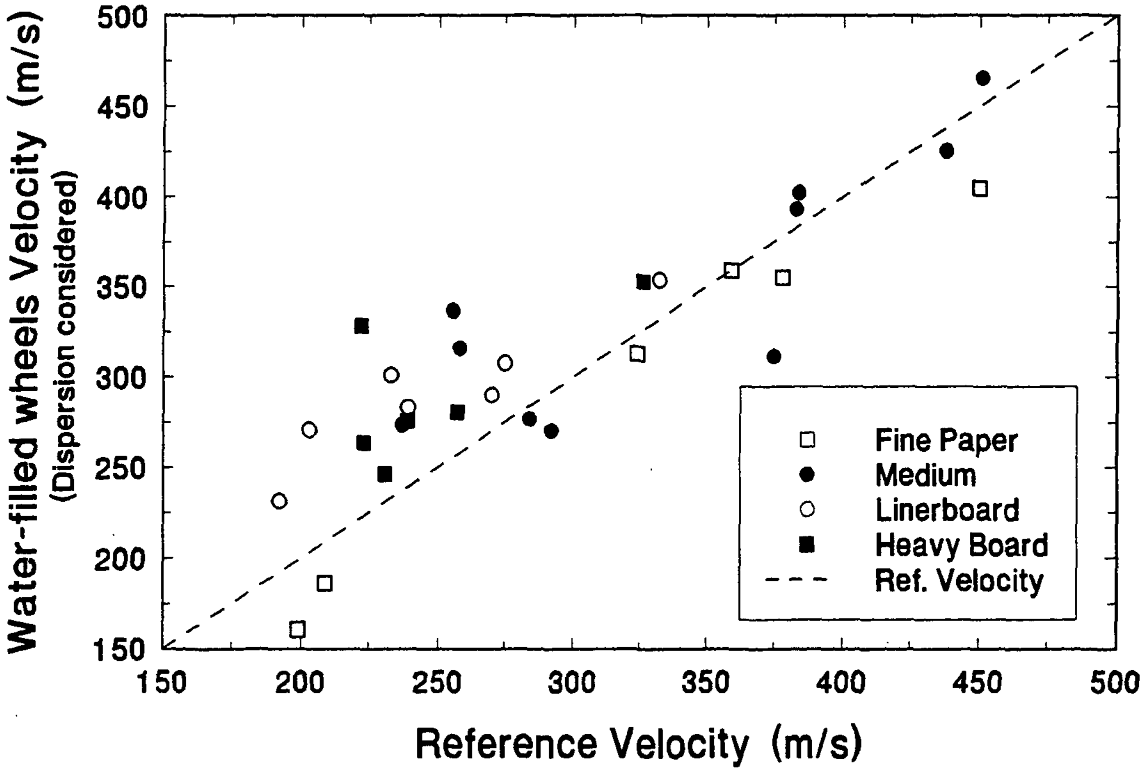

Figure 5. Dispersion corrected WFW velocity vs. reference velocity.